REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
24-10-2011	Briefing Charts	

4. TITLE AND SUBTITLE

The Effect of Swirl on Gas-Centered Swirl Coaxial Injector Sprays

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Malissa D.A. Lightfoot, S.Alexander Schumaker, Stephen A. Danczyk and Larry Villasmil

5d. PROJECT NUMBER

5f. WORK UNIT NUMBER

50260538

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RZSA
10 E. Saturn Blvd.
Edwards AFB CA 93524-7680

8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-RZ-ED-VG-2011-427

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RZS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)

AFRL-RZ-ED-VG-2011-427

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited (PA #11924).

13. SUPPLEMENTARY NOTES

For presentation at the JANNAF Joint Subcommittee Meeting, Huntsville, AL, 5-9 Dec 2011.

14. ABSTRACT

Gas-centered swirl coaxial injector design criteria and scaling laws have been developed by AFRL over the last several years. These studies have predominately focused on the measurement and behavior of the liquid film and its relation to atomization efficiency. The spread and quality of the spray as well as its stability have received less attention. These parameters are the focus here and are shown to support the conclusions drawn from the liquid film studies. The spray width is used as the primary metric as the effects of swirl level, momentum flux ratio, liquid flow rate and inlet size/number are examined. The results suggest that the designer should aim for higher levels of swirl and momentum flux ratio and lower liquid mass flow rates to produce more stable sprays with better atomization.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Dr. M.D.A. Lightfoot
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	**Unclassified**	**Unclassified**	SAR	23	N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

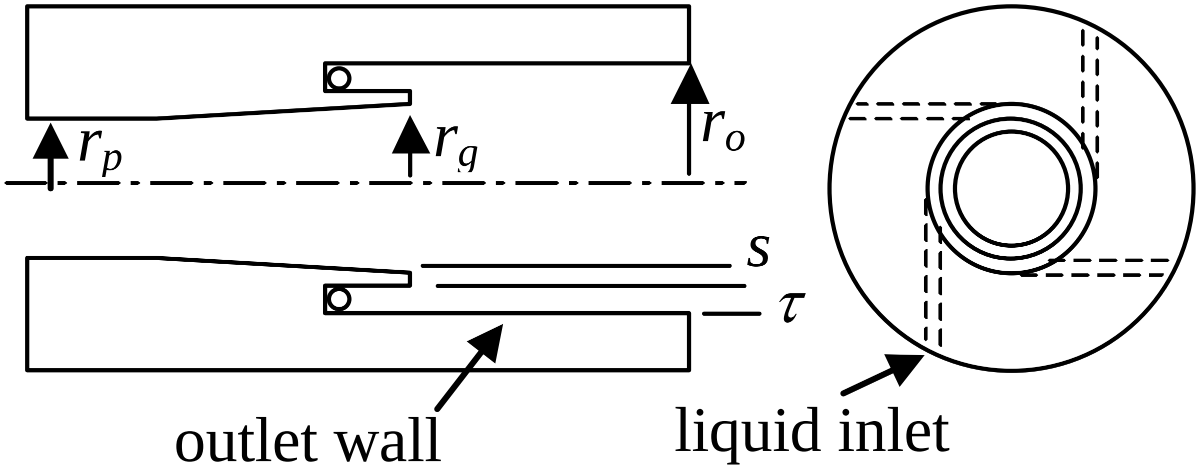
THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

THE EFFECT OF SWIRL ON GAS-CENTERED SWIRL COAXIAL INJECTOR SPRAYS

8 November 2011

Malissa D.A. Lightfoot
Larry A. Villasmil
S. Alexander Schumaker
Stephen A. Danczyk

Gas-Centered Swirl Coaxial Injectors



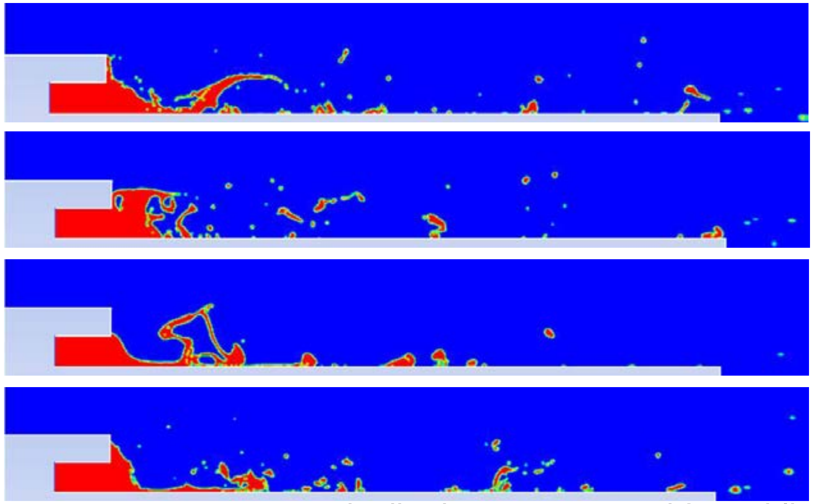
- **Swirling, annular liquid with an unswirled central gas**
- **Used for ox-rich cycles involving liquid hydrocarbons**
  - Design criteria not well established prior to US studies
  - AFRL-developed design criteria and scaling laws
- **Here nitrogen and water used as simulants**

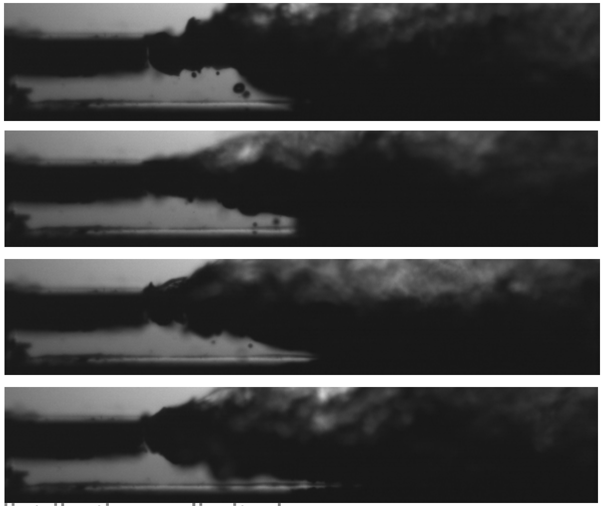
Prior Work

- **AFRL has published prior work on scaling and some design criteria for these injectors**
  - Focused on atomization efficiency which is related back to film length
  - Film length scales with momentum flux ratio ($\rho_g v_g^2/\rho_l v_l^2$)
    - Must calculate using compressibility of the gas
    - Use total velocity for liquid
  - Momentum flux ratio is dominant parameter
    - Other nondimensional parameters are at least two orders of magnitude smaller
    - Centripetal forces (swirl effects), through a “Pseudo-Froude” number, are next important
  - Operate at large momentum flux ratios for best atomization and stability

CFD of the Film

- **In addition to experimental focus on film length, modeling has also been started**
- **Modeling a two-phase in high turbulence and with high shear is a challenging problem**
  - Qualitative similarities can be obtained for the very unsteady, no liquid swirl case
    - Film length is very unsteady and large disturbances are observed on the surface



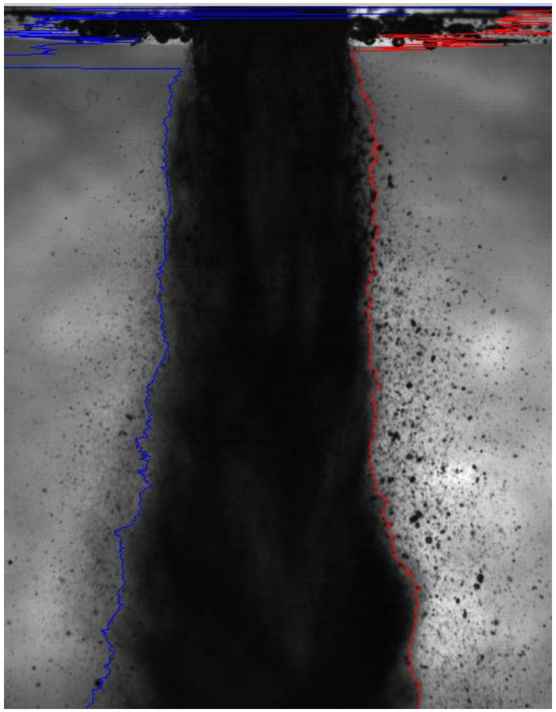


CFD of the Film

- **Several lessons learned from these simulations**
  - Grid independence established for single-phase gas flow
    - Grid independence is nontrivial (possibly impossible) to achieve with a boundary present
  - Small changes in gas-phase upstream boundary condition can cause unrealistic hypersonic flow in the injector cup
    - Running simulations to get fully-developed turbulent velocity profiles is not necessarily sufficient
  - Best turbulence model for single-phase flow is k-epsilon
  - Necessary to do explicit time stepping due to large gradients and changes (slow)
- **Better agreement may require LES modeling which will, in turn, require performing three-dimensional simulations**

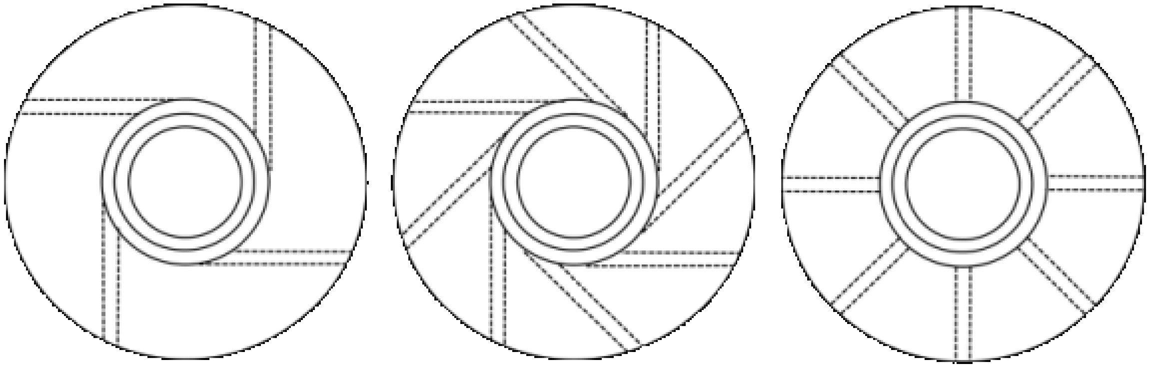
Current Focus—Sprays and Swirl

- **Earlier work has been predominately focused on the film at a single swirl number**
  - Swirl impact on films presented at the AIAA Joint Propulsion Conference (AIAA 2011-5621)
- **Current work focuses on sprays with measurements from backlit shadowgraphy**
  - Metrics are atomization quality (qualitatively), width and instability (variability) of spray
    - Atomization quality not available quantitatively due to large optical densities of these spray



Geometry

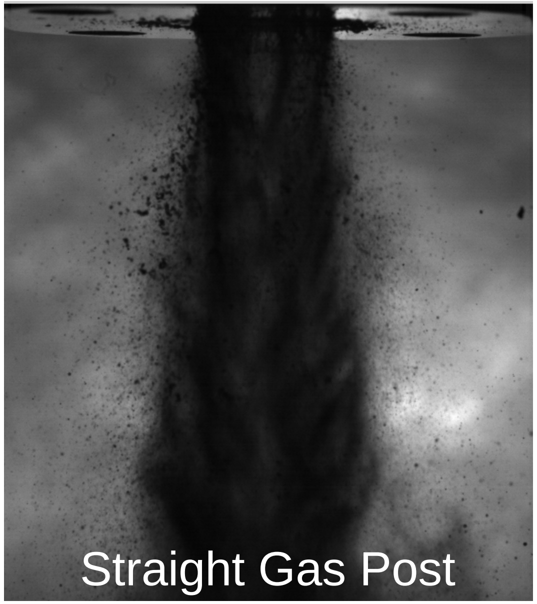
- **Three different swirl levels (altered by liquid inlet geometry) were examined along with a no-swirl case**

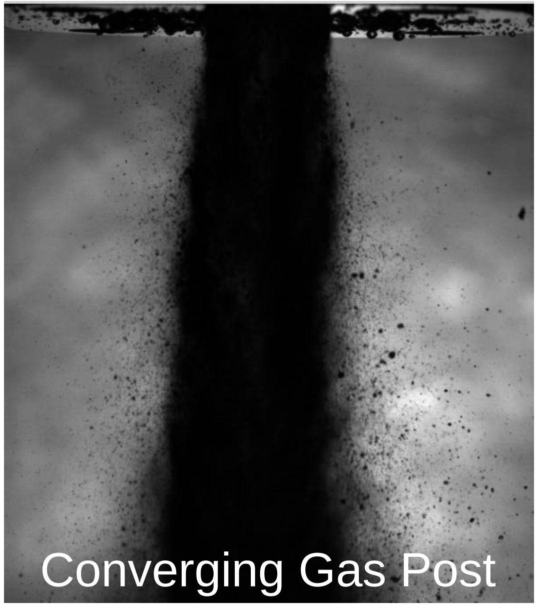


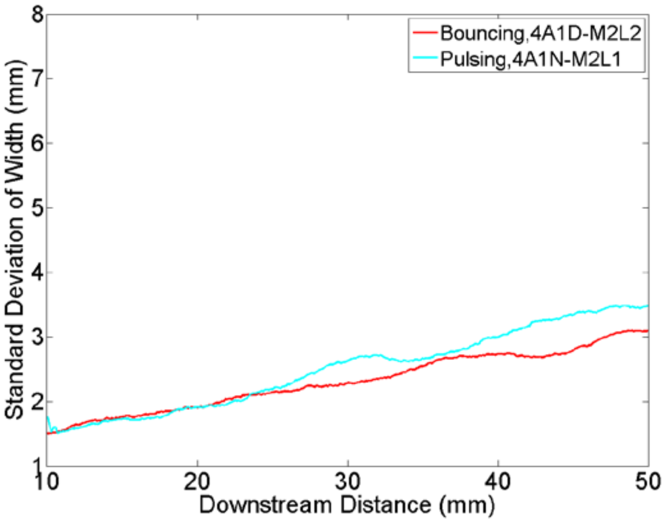
- **Also changed is the lip geometry prior to gas-liquid contact (either a straight gas post or a slightly convergence in the gas post)**
- **Only 8 cases are considered in this preliminary examination**
  - Effects of the above geometry changes plus changes in momentum flux ratio and liquid mass flow rate examined

Internal Geometry

- **Cannot be varied completely independently (liquid flow rate changes to maintain momentum flux ratio)**
- **As expected, a change in the character of the instability of the spray was observed**
  - However, variability amount, as shown through standard deviation in the width, is very similar





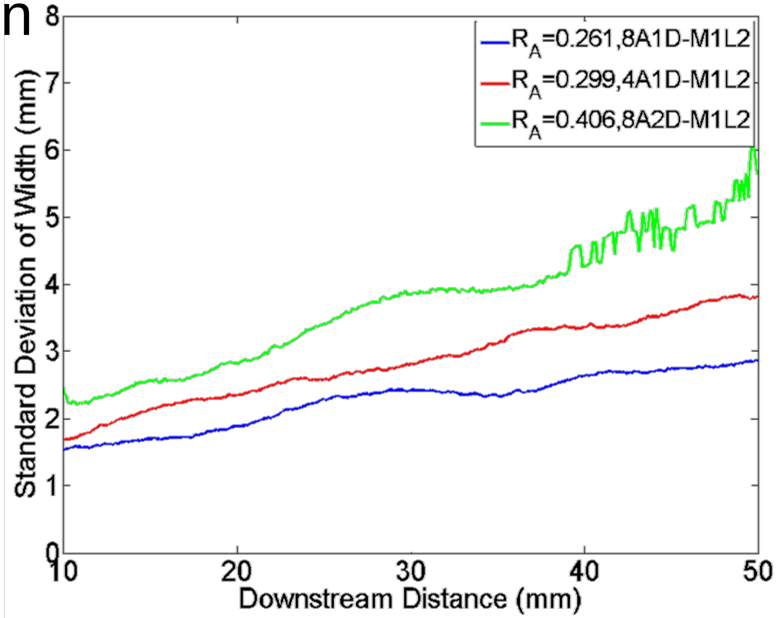


Swirl Number Expectations

- **The "traditional" swirl number ratioing the tangential to total velocity is not useful here**
  - All are very near 1 or 0
  - Instead the ratio of axial to total velocity (R_A) is used. As it increases, swirl decreases
- **Expectations of swirl's effect**
  - Earlier film studies show the film length has little change with swirl (above a no swirl case), so no change in atomization quality would be predicted
  - As swirl increases, and the film has more tangential velocity, its width might be expected to increase as it does for a pressure-swirl atomizer
  - Since swirl stabilizes the film, lower R_A should be more stable

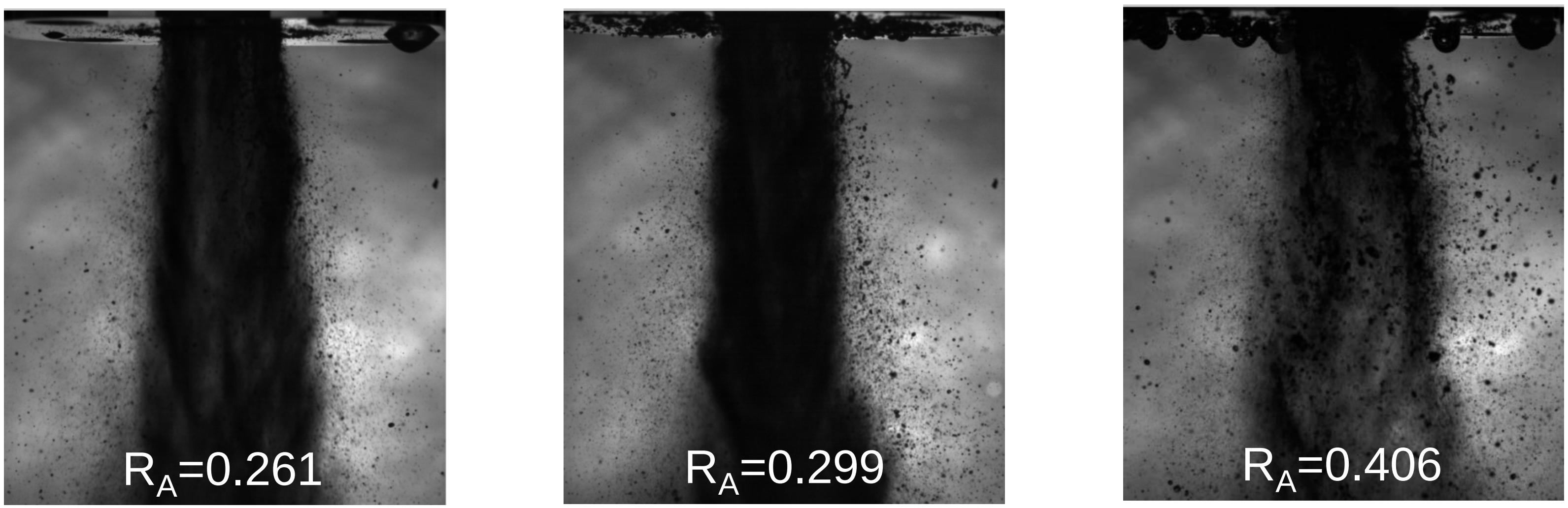
Swirl Number Effects

- **Film width does not change a measurable amount (there is some change but this is below the measurement uncertainty)**
  – This may be due to the relatively small differences in tangential velocity
  – The no-swirl case does not have a “dark core” so its width is not measurable for comparison
- **Film unsteadiness, as evidenced by standard deviation in width, increases as swirl decreases**
  – General character of instability stays the same



Swirl Number Effects

- **Despite film length not being altered by swirl, the atomization quality is**
  - Greater residence time of liquid due to swirl could be a potential cause, since scaling is done using total velocity



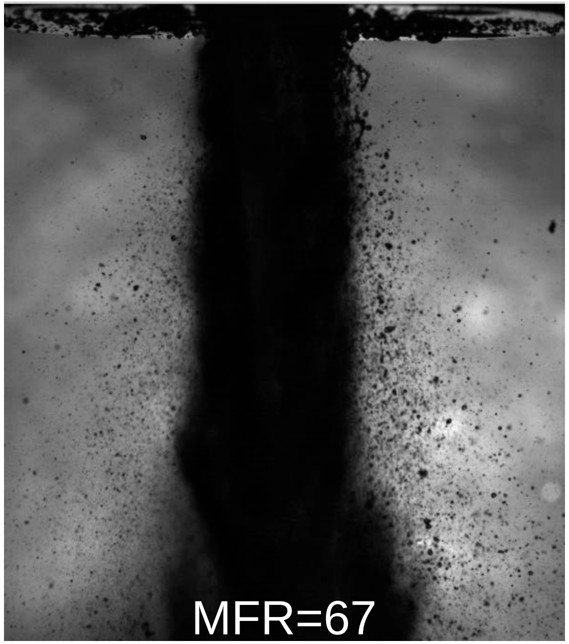
- **Overall initial recommendation for engines: Run at elevated swirl levels to increase the stability of the atomization (should also improve atomization slightly)**

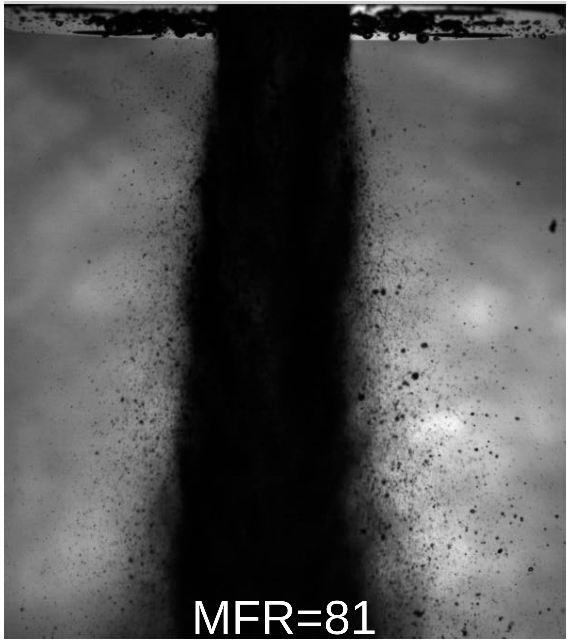
Momentum Flux Ratio Expectations

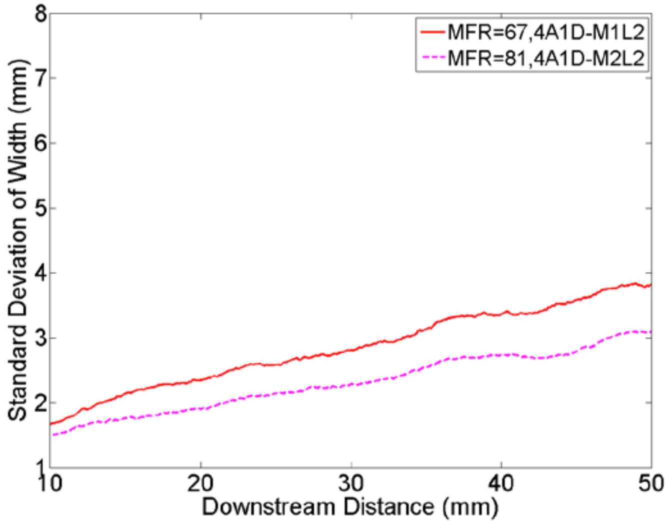
- **Momentum flux ratio was altered while the liquid flow rate and swirl were constant**
- **Expectations of changes with momentum flux ratio**
  - From film studies, it is expected that atomization quality decreases as momentum flux ratio decreases because the film length increases as the ratio decreases
  - Also from film studies, the instability should increase as momentum flux ratio decreases
  - There is no reason to expect that the film width would be effected by the momentum flux ratio

Momentum Flux Ratio Effects

- **Atomization quality does indeed decrease as momentum flux ratio decreases**
- **The instability (shown through the width standard deviation) does increase as momentum flux ratio decreases**
  - The unsteadiness also changes in character

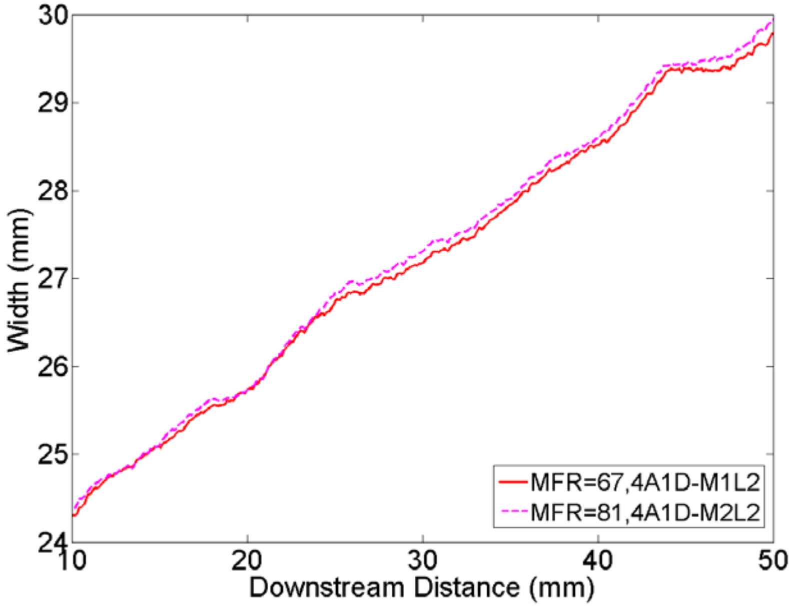






Momentum Flux Ratio Effects

- **The film width is unaffected by the momentum flux ratio**



- **Overall initial recommendation for engines: Run at elevated momentum flux ratios to improve mixing and stability of the spray**

Liquid Mass Flow Rate Expectations

- **Liquid mass flow rate was not varied independently in the current set of experiments**
  - Tests where lip geometry changes also
  - Other set where swirl also changes
- **Expectations of changes when liquid mass flow rate is altered**
  - Film results would suggest that atomization quality should not change as long as the momentum flux ratio is constant
  - Also from film work, there is no reason instability should be altered, again assuming momentum flux ratio is constant
  - Pressure-swirl atomizers have increased width with increased flow rate, but they atomize outside the injector—it is unclear if this would translate to GCSC injectors

Liquid Mass Flow Rate Effects

- **Atomization quality does not appear to be impacted**
  - No difference with a 30% change in flow rates and a change in geometry
  - Impacted when swirl number was changed with a 50% change in flow rates; however, differences not obviously greater than with swirl alone

RA=0.261, m_l=36.2 g/s

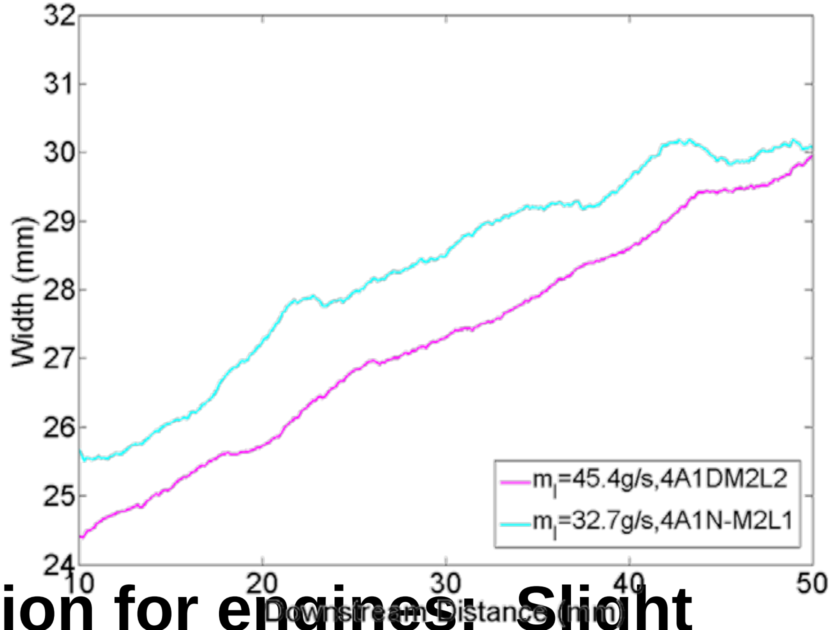
RA=0.406, m_l=60.4 g/s

Straight Post, m_l=32.7 g/s

Converge Post, m_l=45.4 g/s

Liquid Mass Flow Rate Effects

- **No dependence of instability on flow rate was observed**
- **Width increased somewhat**
  - Greater with change in lip geometry versus change in swirl for the two sets here
  - May be due to more mass in the core of the spray making the dark core appear larger



- **Overall initial recommendation for engines: Slight improvements in interelement mixing may be possible by increasing liquid flow rate; care should be taken if liquid flow rate is greatly altered during throttling**

Number of Inlets

- **Not varied independently, but two geometries with R_A very close**
- **No reason to expect inlet number or size (independent of swirl) should change the spray**
  - Essentially no effect on pressure-swirl atomizers
- **No effects were observed here**
- **Overall initial recommendation for engines: Designer has flexibility to optimize swirl and size of inlet holes (to minimize clogging, etc. dangers)**
  - Some research suggests staggering sets of hole helps ease feedback and combustion instabilities

Conclusions

- **Scale modeling and design criteria of GCSC injectors has been accomplished previously**
- **Building on this work, some initial CFD of the film was started**
  - Some qualitative behaviors have been achievable but quantitative comparisons remain elusive
- **Shadowgraphy of the spray from a GCSC injector was the main focus of this work**
  - Several parameters were varied to observe their effect on the spray and make design recommendations
  - Results are based on a relatively small number of tests, so they are preliminary

Conclusions

- **The shadowgraphy studies have resulted in the following preliminary recommendations for design**
  - Internal geometry can be used to alter the type of instabilities the spray exhibits at certain momentum flux ratios
  - Elevated swirl levels are preferential to improve stability (and atomization slightly)
  - Higher momentum flux ratios improve mixing and stability of the spray
  - Because width does increase somewhat with liquid mass flow rate, care should be exercised when throttling if the flow rate is altered greatly
  - The designer has flexibility on the size and number of liquid inlets (assuming swirl is kept high)

Back up Slides

Test Geometries and Conditions

Geometry Name	Lip Height (mm)	Inlet Area (mm^2)	Inlet Number	R_A
8A1D	2.41	7.50	8	0.261
4A1D	2.41	7.54	4	0.299
4A1N	1.52	7.54	4	0.299
8A2D	2.41	15.1	8	0.406
NSD	2.41	7.50	8	1.000

Outlet Radius, r_o	9.53 inch
Gas Post Radius, r_p	12.7 inch
Injector Cup, L_o	31.7 inch
Sheltered Length, L_s	3.17 inch
Initial Film Thickness, τ	1.65 inch

Test Name	m_g (g/s)	m_l (g/s)	MFR	R_A
8A1D-M1L2	66.8	45.1	62	0.261
8A2D-M1L2	32.1	45.3	63	0.406
4A1D-M1L2	57.3	45.8	67	0.299
8A1D-M2L1	56.9	36.2	81	0.261
4A1D-M2L2	67.1	45.4	81	0.299
8A2D-M2L2	65.2	60.4	82	0.406
NSD-M2L1	8.5	27.6	84	1.000
4A1N-M2L1	59.1	32.7	88	0.299